Ocean Acoustics and Signal Processing for Robust Detection and Estimation

Zoi-Heleni Michalopoulou
Department of Mathematical Sciences
New Jersey Institute of Technology
Newark, NJ 07102
phone: (973) 596 8395   fax: (973) 596 5591   email: michalop@njit.edu

Award Numbers: N000140510262, N000140710521
http://www.math.njit.edu/~elmich

LONG TERM GOALS

The long term goal of this project is to develop efficient inversion algorithms for successful estimation and detection by incorporating (fully or partially) the physics of the propagation medium. Algorithms will be designed for geoacoustic inversion and also for robust ASW localization and detection.

OBJECTIVES

- Achieve accurate and computationally efficient source localization by designing estimation schemes that combine acoustic field modeling and optimization approaches.
- Develop methods for passive localization and inversion of environmental parameters that select features of propagation that are essential to model for accurate inversion.

APPROACH

Arrival times and amplitudes of distinct frequencies (within a single mode or across different modes) provide a wealth of information on environmental properties of the propagation medium and source location. Demonstration of the role of modal arrival times and amplitudes in geoacoustic inversion and source localization has been discussed in [1, 2, 3, 4].

Typically, extraction of modal information from the reception of signals that have traveled long distances in dispersive underwater environments is performed with time-frequency or wavelet analysis [5]. Accurate identification of modes and their amplitudes and arrival times is, however, challenging. The uncertainty in the process has an impact on the accuracy of geoacoustic inversion and source localization, which has not been, to date, quantified.

In this work, a method is developed for modal decomposition of a received signal and modal arrival time estimation. The method employs principles of dynamical systems for multiple source tracking [6] and applies those to the extraction of "frequency trajectories" from spectrograms of received signals [7, 8, 9]. Every mode in the short time Fourier transform representation of the signal is treated as a distinct source track with small changes in location (frequency, in our case) at each time step. We generate a particle filter that exploits two relationships, one for frequency updating vs. time (state equation) and the second one for comparison of the Fourier transform representation of a synthetic signal for the chosen state to that of the true signal (observation equation). After a few initial steps, the particle filter identifies distinct "tracks" and reports probability distributions around them. The

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14. ABSTRACT

The long term goal of this project is to develop efficient inversion algorithms for successful estimation and detection by incorporating (fully or partially) the physics of the propagation medium. Algorithms will be designed for geoacoustic inversion and also for robust ASW localization and detection.

15. SUBJECT TERMS

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method also estimates the number of tracks (modes) present at each time using a stochastic mechanism that allows modes to "be born" or expire.

The approach, developed in collaboration with Ivan Zorych (postdoctoral fellow at NJIT, 2006-2008), provides more reliable estimates than conventional short-time Fourier transform analysis; it, furthermore, allows the computation of posterior probability distributions for arrival times, which can be then used for uncertainty estimation in geoacoustic inversion.

In parallel, we explored how similar approaches can improve arrival time estimation; the ultimate is again accurate inversion, where the uncertainty in arrival times provides insight into the uncertainty in geometry/environment characterization (work done in collaboration with Rashi Jain, Ph.D. student, ONR Graduate Traineeship recipient). We developed a particle filter-based approach where we jointly estimate arrival times at a set of hydrophones, taking into account possible variations of arrival times at spatially separated phones. This process allows us to substantially reduce the error in arrival time estimation and facilitates the calculation of probability distributions for these arrivals (which are not always Gaussian as often assumed in inverse problems).

WORK COMPLETED

The described arrival time estimation approaches were designed and applied to synthetic and real data. For the dispersion analysis, the synthetic data simulated received signals propagating in a shallow water environment and traveling a distance of 20 km away from the source. The frequency content of the signals was between 200 and 600 Hz. For the arrival time estimation of multipaths, we simulated signals received at a set of vertically separated receivers at a relatively small distance (~1000 m) from the source. Tests are underway with ASIAEX, Haro Strait, and Gulf of Mexico data sets.

In addition to modal arrival time estimation from dispersion analysis, geoacoustic inversion was conducted using the estimates of the particle filter tracking approach. Also, geometry, bathymetry, and sound speed inversion was carried out, employing the multipath arrival times extracted with our technique.

RESULTS

Figure 1 presents the spectrogram of a synthetic received signal. Dispersion curves corresponding to several modes can be clearly identified; some modes are, however, not that clear.

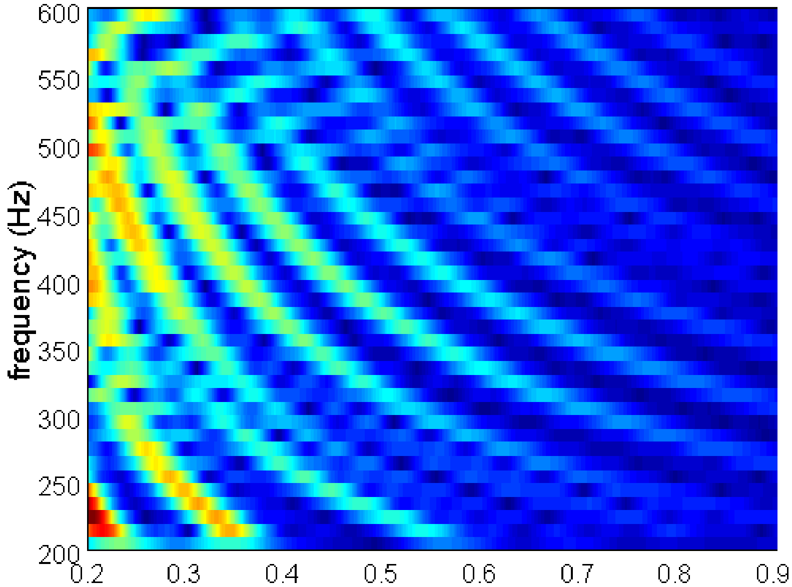

Figure 1: Spectrogram of a signal that has propagated 20 km from the source in a shallow water environment. The frequency content of the signal was between 200 and 600 Hz.

Figure 2 demonstrates the local maxima selected from the spectrogram of Figure 1, by setting thresholds that determine the presence or absence of a mode. Although some general features on the modes are clear, we can see that not all modes can be tracked without interruption. In addition, there are several ambiguous local maxima that could signify either the presence of modes that are very poorly identified or noise. On the same figure, we have superimposed numerically calculated dispersion curves for the modeled waveguide (blue curves) and tracks calculated via particle filtering (green).

The comparison shows a close match between estimated tracks and true dispersion curves. The new process identifies modes that are missed in the local maximum process; modes that were highly ambiguous in the results of the conventional approach are now clearly outlined. Because the particle filtering method is based on short-time Fourier transforms, the resolution is dictated by the length of the time window that is used and cannot be increased without a penalty on time resolution. There are, however, extensions of the new approach that are currently being implemented towards a frequency resolution improvement.

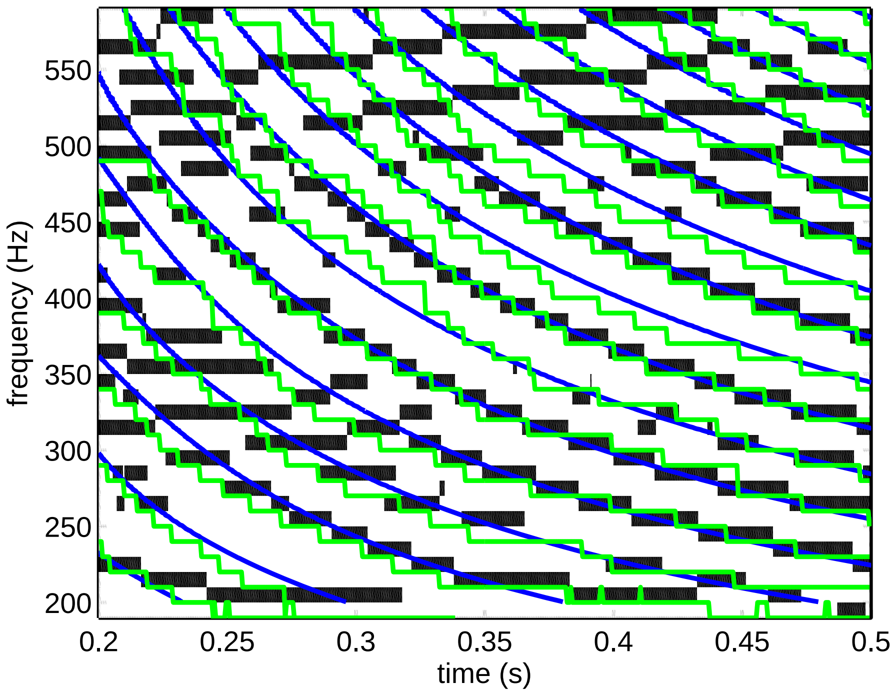

Figure 2: Mode selection with local maximization from the spectrogram of Fig.1 (black), numerically calculated dispersion curves (blue), and tracks estimated via particle filtering (green).

The particle filter process is Bayesian is nature and calculates posterior probability distributions of frequencies within a mode and across different modes being present at a given time. This property allows us to probabilistically quantify uncertainty in the estimation process. This uncertainty can then be propagated through an inversion process to produce uncertainty estimates on geoacoustic parameters. Probability distributions of arrival times for a single frequency across multiple modes are shown in Figure 3.

Figure 4 presents the "slice" $p(c_0 \mid \mathbf{t})$ from the probability distribution $p(c \mid \mathbf{t})$, where c is the compressional sound speed in the sediment, c_0 is the *true* compressional speed in the sediment, and $\mathbf{t}$ are arrival times for two modes extracted with the particle filter/time-frequency method. The figure illustrates how this probability is a function of the estimates of the two modal arrival times and the uncertainty in this estimation.

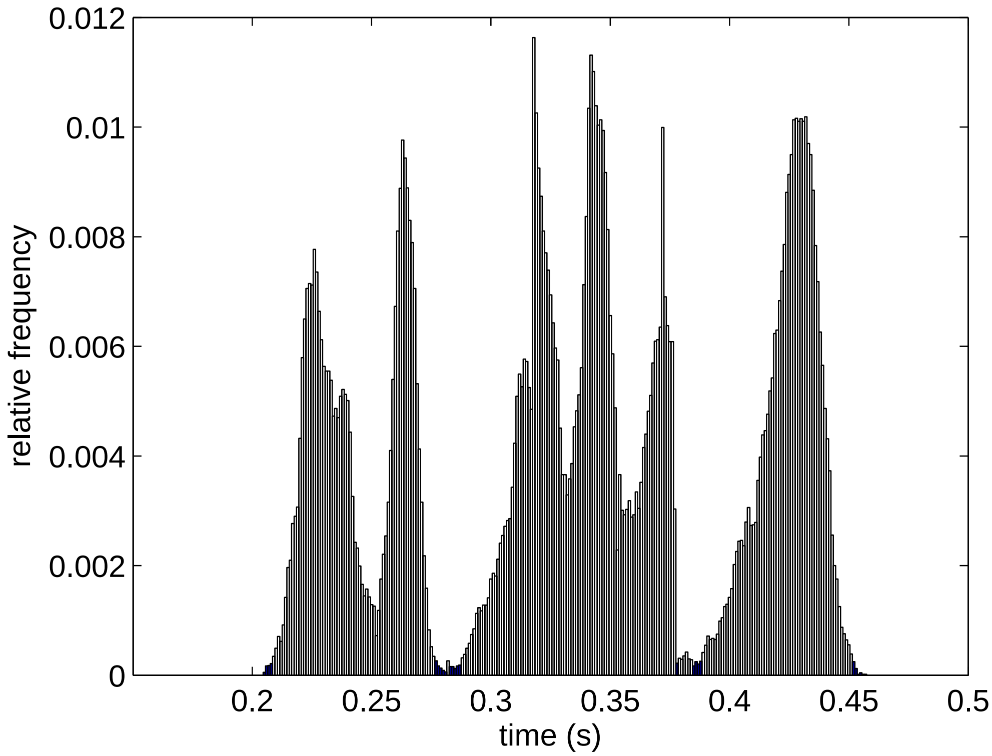

Figure 3: Probability distribution of modal arrival times at 410 Hz estimated via the particle filtering tracking process.

Figure 5 demonstrates results from a similar approach as applied to short-range time-series for arrival time estimation of distinct multipaths. The figure presents mean squared error in arrival time (in time samples) vs. number of particles for two different particle filtering techniques implemented here and compares this error to a standard Maximum Likelihood (ML) approach. Arrival time error is much smaller with the dynamic methods, exploring spatial variability constraints across hydrophones.

IMPACT

The significance of accurate arrival time estimation in geoacoustic inversion has been extensively studied with several methods designed for producing geoacoustic parameter estimates and measures of the uncertainty in the estimation process. The reliability of these methods is intimately tied to the ability of accurately extracting and identifying arrival times. The new methods facilitate this extraction, also producing posterior probability distributions of arrival times, which can then be used to quantify uncertainty in the estimation of geoacoustic parameters.

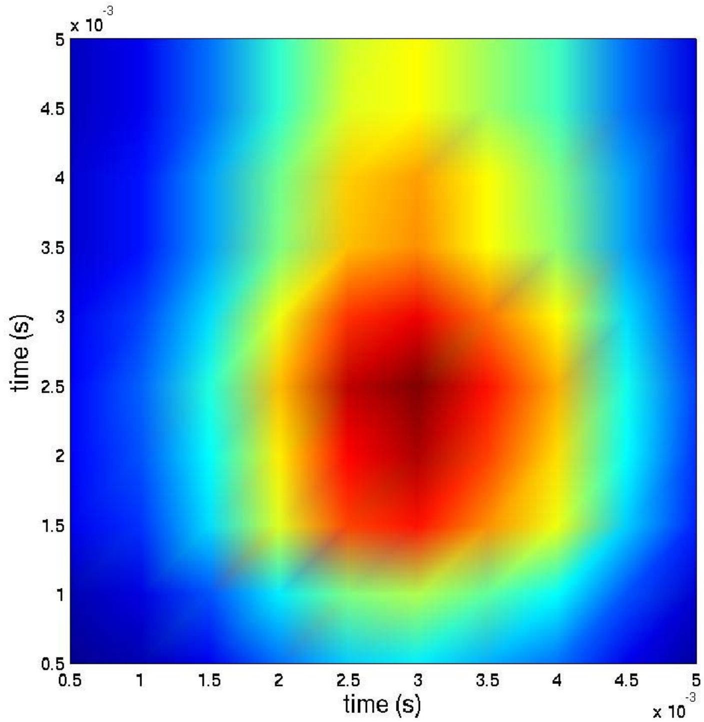

Figure 4: Probability p(c0/t) vs. arrival times for two modes as estimated by the tracking algorithm.

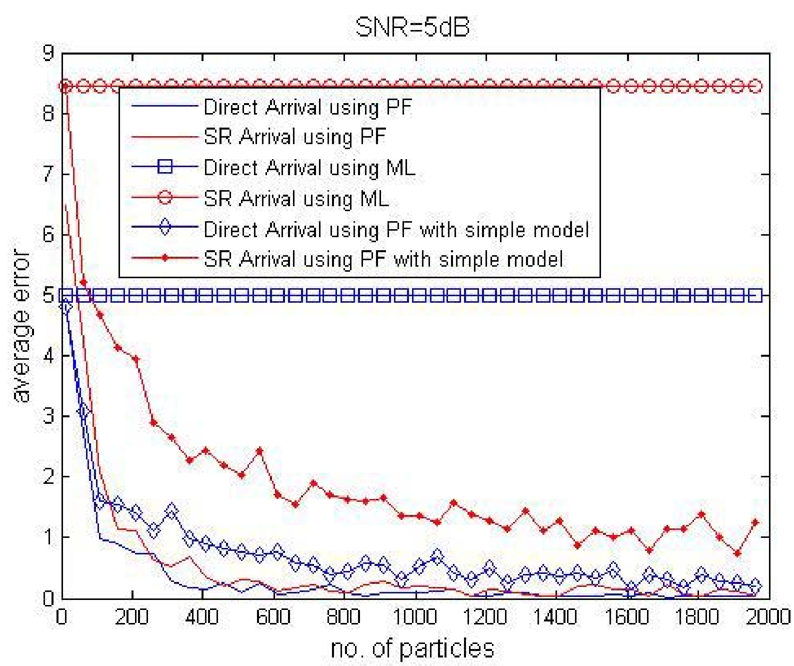

Figure 5: Arrival time error calculated by particle filtering compared to error calculated by standard ML estimation for an SNR of 5dB.

RELATED PROJECTS

A collaboration is underway with Dr. Lisa Zurk (Portland State University) on developing a particle filter tracker introduced in this project for active target tracking employing the invariance principle [10].

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HONORS/AWARDS

- Albert Dorman Honors College Excellence in Teaching Award, May 2008
- Master Teacher Award, New Jersey Institute of Technology, September 2008